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The features and influential factors of interactions among ecosystem services

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ABSTRACT

Understanding the impact of climate change and human activity on the interactions among ecosystem services and associated characteristics is critical to improve ecosystem management and achieve regional sustainability. We respectively used Carnegie-Ames-Stanford Approach, Revised Wind Erosion Equation, and the integrated valuation of ecosystem services and tradeoffs (InVEST) model to evaluate the amount of net primary productivity (NPP), soil erosion by wind (SL), and soil conservation (SC), water yield (WY), and water retention (WR) from 2001 to 2014 in the Xilin Gol grassland of North China. A segmented quantile regression approach was used to extract the constraint lines, which are the upper boundaries of the scatter plots of paired ecosystem services and represent the constraint effects between them. The thresholds, slopes, and constant terms of the regression equations were used to characterize the key features of the constraint lines. Finally, we analyzed the correlation between the key features and the influential factors of climate as well as the Normalized Difference Vegetation Index (NDVI). The results showed that the patterns and the thresholds of constraint lines between ecosystem services were almost invariable with the changing of climate factors and NDVI from 2001 to 2014. However, the key features of slopes and constant terms on the constraint lines were easily impacted by the environmental factors. As precipitation is the main source of water requirements of vegetation in the arid and semiarid regions and affects the variations of NPP, SC, WY, and WR, the precipitation factors appeared to be critical to shape the constraint lines and determine the strength of constraint effects between paired ecosystem services. Understanding the changing trends of key features on the constraint lines between paired ecosystem services and their influential factors could improve the quantitative management measures of ecosystem services and promote sustainable land use planning.

1. Introduction

Ecosystem services, the benefits that people obtain from nature, are currently an important consideration in ecosystem management and landscape optimization (de Groot et al., 2010; Wong et al., 2015; Wu, 2013). Under the pressures of climate change and human disturbance of the environment, global ecosystem services are declining (Costanza et al., 2014; White et al., 2000). Changing the supply in a subset of ecosystem services would result in the decrease of others because of their complex interactions (Bürgi et al., 2015). Managing human activities based on the complex interaction is critical to maintain the provision of ecosystem services and improve regional human wellbeing (Fezzi et al., 2015; Howe et al., 2014; Wu, 2013). There may be thresholds for the interrelation curves among ecosystem services (Aguiar and Sala, 1999; Carpenter and Brock, 2006; Hao et al., 2017b). On the two sides of the thresholds, the structures, functions, and services of ecosystems exhibit large differences (Bestelmeyer et al., 2013; Scheffer and Carpenter, 2003). The pressures of climate change and the improper utilization of natural resources can both possibly push ecosystems from one side of the threshold to the other side (Katwijk et al., 2016; Maestre et al., 2016; Roodposhti et al., 2017). Therefore, determining the changing trends of key thresholds and their influential factors can help predict the future states of ecosystem services based on whether policy makers can formulate timely remedial or adaptive measures (Carpenter and Brock, 2006; Folke et al., 2002).

However, little research has focused exclusively on the thresholds of interaction among ecosystem services and explored the underlying influential factors. Currently, when ecosystems services are related to one another, the relationship can take the form of tradeoffs, synergies, or constraint effects (Bennett et al., 2009; Hao et al., 2017b; Lester et al., 2013). Ecologists are exploring the underlying ecological mechanisms and drivers of these relationships (Bennett et al., 2009), but ongoing

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studies lack quantitative analysis. The main reasons for this gap are as follows: 1) Among a variety of statistical methods to study the relationships among ecosystem services, the correlation coefficient is one of the most commonly used indicators (Jopke et al., 2015; Raudsepp-Hearne et al., 2010). However, the correlation coefficient is easily affected by the number and distribution of samples and only reflects general trends of scatter among paired ecosystem services (Raudsepp-Hearne et al., 2010; Thomson et al., 1996). Therefore, it is difficult to obtain stable results and explore the underlying ecological mechanisms and drivers; 2) There are multiple factors, including climatic factors and land use/cover change that impact the provision of ecosystem services and their relationships (Albert et al., 2016; Fu et al., 2017; Hao et al., 2017a). 3) It is not possible to capture the key features of interactions among ecosystem services using traditional linear-based statistical approaches (Feng et al., 2017; Fu et al., 2017). The constraint effect between paired ecosystem services, indicating that one service is constrained by the other one with less or almost no constraint by any other factors, was proposed to reveal their nonlinear relationships, thresholds, and relevant potential ecological processes (Hao et al., 2017b). The analysis of a long time series can provide us with the ability to test the stability of the constraint effect among paired ecosystem services and promote the understanding of its features and underlying influential factors (Piao et al., 2006; Raynolds et al., 2008).

Grassland is one of the most important terrestrial ecosystems, and its extensive distribution supports a large human population (White et al., 2000). Grassland can provide numerous and varied ecosystem services, including livestock products, climate regulation, and recreation (Lamarque et al., 2014; Yahdjian et al., 2015). Grassland in northern China is an important part of the global grassland ecosystem. However, as a vulnerable and sensitive ecosystem, grassland in northern China is suffering from drying and a warming climate as well as overgrazing (Zhang et al., 2016). To restore the degraded grassland, several ecological conservation projects, such as the Grain for Green Project and the Beijing-Tianjin Sandstorm Source Control Project, have been launched (Cao et al., 2009). Xilin Gol is one of the main areas where the projects are implemented. Since 2000, the landscape pattern in Xilin Gol has changed substantially, and the key ecosystem services, including net primary productivity, soil conservation, and water retention, have improved to some degree (Deng, 2009; Hao et al., 2017a). The changing environment in Xilin Gol provides a good case study to explore the features and influential factors of the constraint effects among ecosystem services.

The three main objectives in the study are: 1) quantifying the constraint effects between paired ecosystem services using a long time series (2001–2014) in Xilin Gol; 2) exploring the change ranges in thresholds and other key features of the constraint effects; and 3) revealing the factors and the influential mechanisms that shape the key features of constraint effect among paired ecosystem services.

2. Materials and methods

2.1. Study area

Xilin Gol is located between 42°32′–46°41′N and 111°59′–120°E and comprises a total area of 200,000 km^2 (Fig. 1). This area has a continental monsoon climate that is characterized by strong winds, drought, and cold temperatures. The average annual temperature and precipitation are approximately 2 °C and 295 mm, respectively. The terrain of Xilin Gol is high in the south and low in the north. The soil types are mainly loam, sand, and sandy loam. The landscape of Xilin Gol consists of almost 90% grassland in 2010. It plays an important role as an ecological barrier to protect North China from sandstorms (Gao et al., 2000). However, the grassland in Xilin Gol is seriously degraded, with a decrease in productivity and an increase in the proportion of desertified area compared to available pasture areas, which expanded from 48.6% in 1984 to 64% in 1996 (Deng, 2009). Since the implementation of the sand control project in 2005 and the Grain for Green Project in 1999, desertification has been suppressed, and the grassland area increased from 176,200 km^2 to 177,100 km^2 by 2009 (Hu, 2013).

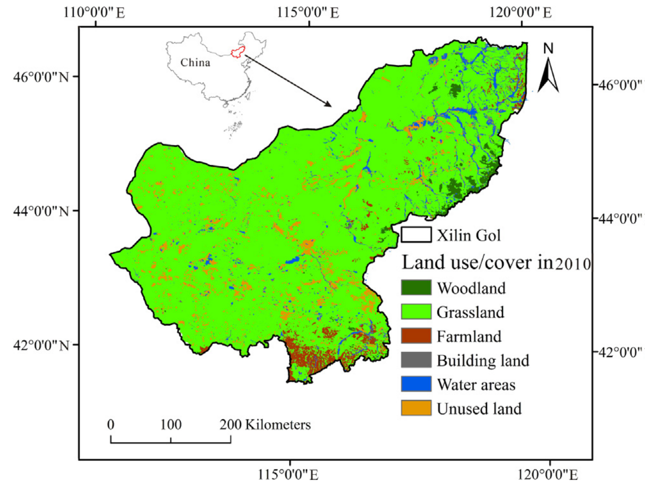

Fig. 1. The location and the land use/cover of Xilin Gol.

2.2. Estimation of ecosystem services from 2001 to 2014

We estimated the total annual provision of four key grassland ecosystem services including net primary productivity (NPP), soil conservation (SC), water yield (WY), and water retention (WR), and one disservice of soil erosion by wind (SL), with a spatial resolution of 250 m from 2001 to 2014. NPP is the organic matter produced by photosynthesis of green plants and was estimated by the Carnegie-Ames-Stanford model (Potter et al., 1993). Soil erosion by wind can result in a substantial decrease in the productivity of farmland and grassland, especially in arid and semiarid regions. In this study, we used the Revised Wind Erosion Equation to assess SL (Fryrear et al., 1998). SC is the mitigation of soil erosion by water, that can result in soil degradation and a decline in land productivity. WY is the difference of precipitation and evaporation and soil infiltration. The amount of water that the ecosystem retains from the precipitation in the canopy, withered leaves, plant roots, and soil is WR. SC, WY, and WR were estimated using the InVEST (Integrated Valuation of Ecosystem Services and Trade-offs) (Sharp et al., 2015). All the models have been parameterized and tested in northern China (Guo et al., 2013; Hao et al., 2017a; Hao et al., 2017b; Zhu et al., 2007). Table 1 gives a brief description of the datasets used to assess the four ecosystem services and one disservice. The details of the model parameterization may be found in our previous study (Hao et al. 2017b). All the meteorological station datasets of radiation (RA), precipitation (PPT), temperature (TEM), and wind speed (WS) were spatially interpolated to a spatial resolution of 250 m using the ArcGIS10.0 platform.

2.3. Extraction of the constraint lines between paired ecosystem services

The constraint effects between ecosystem services were first proposed by Hao et al. (2017b) and represented by the upper boundaries of the scatter plots of paired ecosystem service. In this study, we adopted the segmented quantile regression (Hao et al., 2017b; Medinski et al., 2010; Mills et al., 2009) to extract the constraint lines of paired ecosystem services (X variable _ Y variable) in Xilin Gol from 2001 to 2014. The ten pairs of ecosystem services in this study are NPP_SC, NPP_SL, NPP_WY, NPP_WR, SC_SL, SC_WY, SC_WR, SL_WY, SL_WR, and WY_WR. The steps to extract constraint lines can be found in our previous study (Hao et al. 2017b). The constraint lines were obtained by fitting boundary points in the Origin 9 software (OriginLab, US) based on the

Table 1
Description of the study data.

Data	Data description (unit)	Data source
Climate data	Daily mean temperature (°C) Daily maximum temperature (°C) Daily minimum temperature (°C) Daily rainfall (mm) Daily mean wind speed (m/s) Daily sunshine duration (h)	China Meteorological Sharing Service System.
DEM	Digital Elevation Model with 90-m spatial resolution (m)	Geospatial Data Cloud, Computer Network Information Center, Chinese Academy of Sciences.
Soil data	Soil texture, topsoil sand fraction, topsoil silt fraction, topsoil clay fraction, topsoil organic carbon	Cold and Arid Regions Science Data Center at Lanzhou.
Land use/cover	Land use/cover in 2000, 2005 and 2010 at 250-m spatial resolution	Infrastructure of Earth System Science.
Normalized Difference Vegetation Index (NDVI)	Monthly NDVI in 2000 with 250-m spatial resolution	Geospatial Data Cloud, Computer Network Information Center, Chinese Academy of Sciences.
Plant evapotranspiration	Plant evapotranspiration for different land use/cover types	InVEST (Integrated Valuation of Ecosystem Services and Trade-offs) User's Guide (Sharp et al., 2015)
Soil roughness	Soil roughness for different land use/cover types	(Fryrear et al., 1998)

scatter cloud shapes of the paired ecosystem services and the goodness of fit values (R^2) (Hao et al., 2017b).

2.4. Quantifying the key features of constraint effect among paired ecosystem services from 2001 to 2014

We suggested twelve types of constraint effects among paired ecosystem services (Hao et al., 2017b) in the Table 2. In this study, the thresholds were used to represent the key features of constraint lines for the following curve types: S-shaped curve, backward S-shaped curve, hump-shaped curve, U-shaped curve, convex-waved curve, and concave-waved curve. The regression coefficients of slopes (k in the Table 2) and constant terms (b in the Table 2) of the constraint lines were used to demonstrate the key features of the monotonic types, which included the positive linear line, negative linear line, positive convex curve, negative convex curve, exponential curve, and logarithmic curve. The slopes (Table 2) represent the strength of the constraint effect between paired ecosystem services. When the slope is greater than 0, the increasing trend of the slope indicates that the constraint effect is weakening. However, when the slope is less than 0, an increasing slope trend indicates that the constraint effect is enhanced. The constant terms (Table 2) represent the position of the constraint lines and determine the strength of constraint effect when the ecosystem services on the *x*-axis are almost equal to 0.

We explored the patterns and possible change ranges (with means ± 1.96 times the standard deviations) of the thresholds in the box plots and dispersion degrees (coefficient of variation (CV) as the absolute values of standard deviations divided by the means) of all the key features on the constraint lines from 2001 to 2014 on the SPSS18.0 platform (IBM, US). In the box plots, the outliers indicate values that are outside of the upper limit (upper quartile plus 1.5 times the interquartile range) and the lower limit (lower quartile minus 1.5 times the interquartile range). The box plots are often used to identify outliers.

Finally, Spearman correlation analysis was adopted to analyze which environmental variables may impact the key features of constraint lines. A constraint line represents the distribution range or potential maximum or minimum of the response ecosystem services with the effect of the constraint services (Hao et al., 2017b). We calculated the means, the maximums, the minimums, and the differences between maximum and minimum of NDVI (Normalized Difference Vegetation Index), RA, PPT, TEM, and WS from the corresponding maps at the pixel level from 2001 to 2014, which were treated as environmental variables in correlation analysis.

3. Results

3.1. The constraint effect among paired ecosystem services from 2001 to 2014

Overall, the constraint lines accurately characterized the boundaries of the scatter clouds of paired ecosystem services, with high goodness of fit values (R^2) (Figs. 2 and A.1 and Table 3). Generally, the shapes of

Table 2
The types of constraint effects between paired ecosystem services, the possible examples, and the corresponding regression models.

Constraint effect type	Possible example	Regression model
Positive linear line	Carbon storage and air quality regulation	y = k x + b
Negative linear line	Livestock and erosion control	
Exponential curve	Air quality regulation and recreation	y = k e^x + b
Logarithmic curve	Erosion control and water yield	y = k ln (x) + b
Positive convex curve	Carbon storage and air quality regulation	y = k x^2 + d
Negative convex curve	Crop yield and water quality	
Hump-shaped curve	Aboveground biomass and erosion control	y = a x^2 + c × + d
U-shaped curve	Flood protection and cultural tourism	
S-shaped curve	Erosion control and crop yield	y = a x^3 + c x^2 + d × + f
Backward S-shaped curve	Aboveground biomass and water yield	
Convex-waved curve	Mitigation of soil erosion by wind and water yield	y = a x^n + c x^(n-1) +…d × + f
Concave-waved curve	Mitigation of soil erosion by wind and water retention	

Note: x and y represent the ecosystem services of independent variable and dependent variable, respectively. k, b, a, c, d, and f are the regression coefficients of different models.

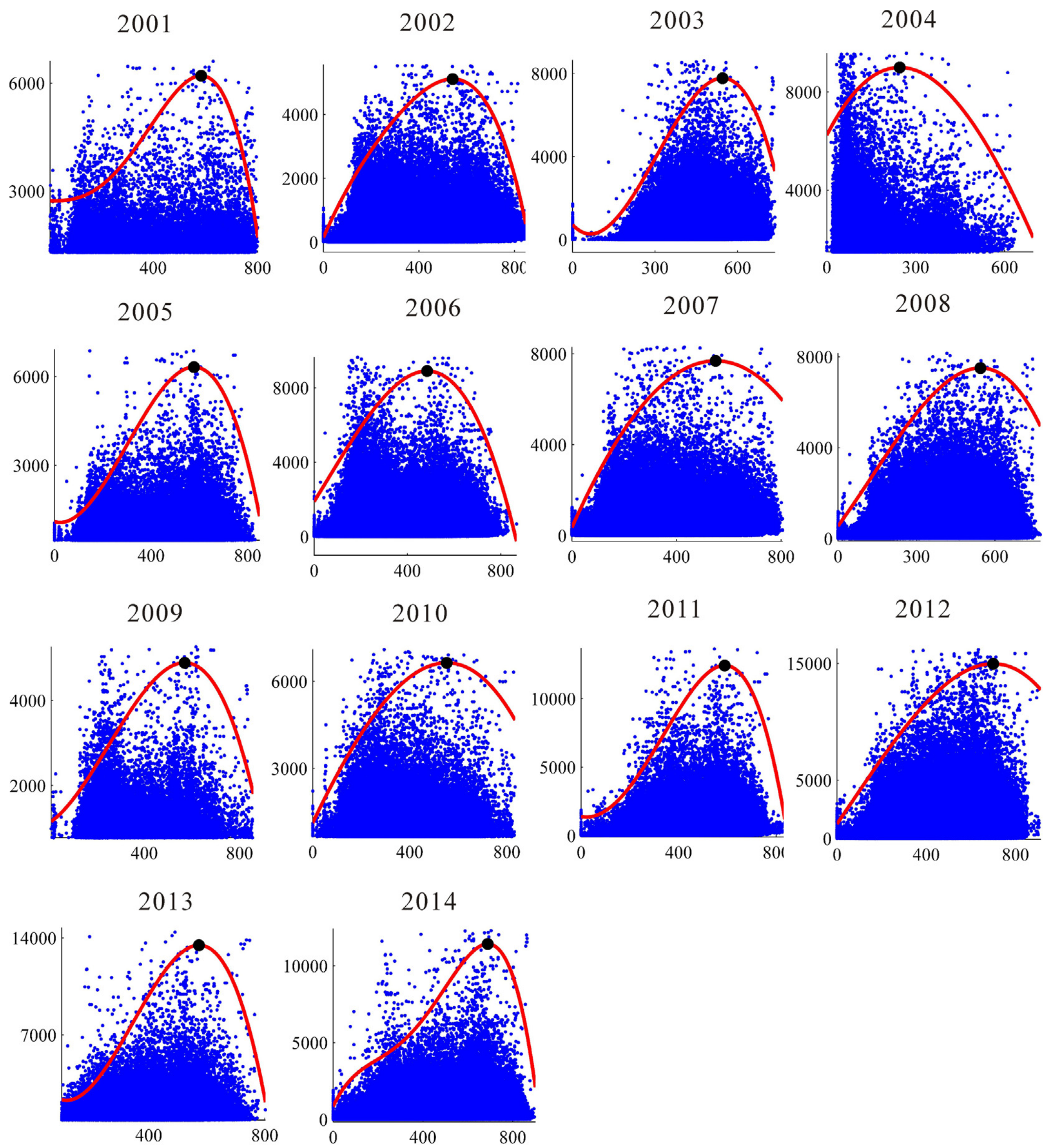

Fig. 2. The scatter clouds (blue points), thresholds (black points), and constraint lines (red lines) between net primary productivity (NPP) in the *x*-axis and soil conservation (SC) in the *y*-axis from 2001 to 2014 in Xilin Gol. The units of NPP and SC are $g\,C\,m^{-2}$ and $t\,ha^{-1}\,year^{-1}$.

Table 3
The goodness of fit values (R^2) of the constraint lines.

	NPP_SC	NPP_SL	NPP_WY	NPP_WR	SC_SL	SC_WY	SC_WR	SL_WY	SL_WR	WY_WR
2001	0.40	0.67 97	0.78 96	0.89	0.77	0.61	0.83	0.80	0.78	0.95
2002	0.57	0.52	0.74	0.88	0.82	0.57	0.82	0.51	0.74	0.85
2003	0.71	0.64	0.75	0.84	0.80	0.41	0.83	0.68	0.64	0.73
2004	0.24	0.93	0.72	0.75	0.85	0.30	0.80	0.65	0.82	0.68
2005	0.60	0.85	0.63	0.62	0.85	0.29	0.75	0.79	0.90	0.65
2006	0.62	0.93	0.78	0.86	0.80	0.31	0.80	0.70	0.90	0.58
2007	0.45	0.87	0.81	0.77	0.78	0.63	0.87	0.77	0.83	0.63
2008	0.51	0.85	0.27	0.77	0.80	0.56	0.87	0.51	0.86	0.99
2009	0.53	0.86	0.57	0.84	0.81	0.62	0.67	0.54	0.68	0.88
2010	0.58	0.93	0.53	0.70	0.74	0.49	0.68	0.76	0.65	0.93
2011	0.65	0.93	0.62	0.86	0.81	0.56	0.77	0.38	0.61	0.95
2012	0.72	0.83	0.65	0.86	0.81	0.58	0.70	0.67	0.78	0.89
2013	0.70	0.86	0.73	0.91	0.71	0.49	0.85	0.66	0.79	0.82
2014	0.65	0.89	0.57	0.77	0.86	0.61	0.72	0.75	0.83	0.94
DF	95 (PE)	98 (SL)	96 (PE)	96 (PE)	98 (LE)	98 (LE)	98 (SL)	98 (SL)	98 (SL)	98 (SL)

Note: DF represents the degree of freedom. PE, SL, and LE are the types of the equation fitted and represent polynomial equation, straight line, and logarithmic equation, respectively. Other details are as in Figs. 2 and 3.

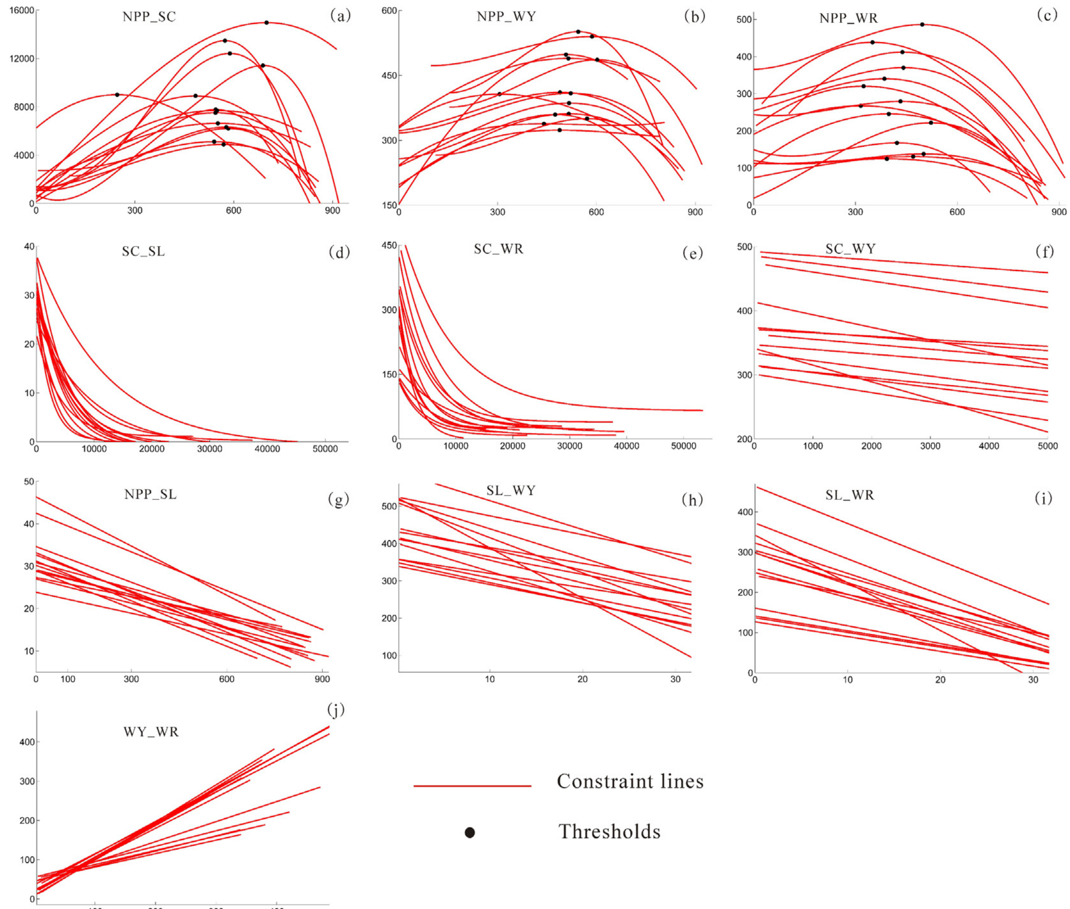

Fig. 3. The constraint lines between paired ecosystem services (X_Y: X represents the ecosystem services on *x*-axis and Y represents the ecosystem services on *y*-axis) and their thresholds (black points) from 2001 to 2014. The units of SL (soil erosion by wind), WY (water yield), and WR (water retention) are kg m^{-2} $year^{-1}$, mm $year^{-1}$, and mm $year^{-1}$, respectively. Other details are as in Fig. 2.

constraint lines were almost unchanged from 2001 to 2014 (Figs. 2 and A.1). The ten paired ecosystem services featured four types of constraint lines, including hump-shaped lines for NPP_SC, NPP_WY, and NPP_WR (Fig. 3a–c), logarithmic lines for SC_SL and SC_WR (Fig. 3d and e), negative linear lines for SC_WY, NPP_SL, SL_WY, and SL_WR (Fig. 3f–i), and a positive linear line for WY_WR (Fig. 3j).

The thresholds on the hump-shaped constraint lines of NPP_SC, NPP_WY, and NPP_WR appeared to vary with time (Fig. 3). On the constraint lines, SC, WY, and WR increased as NPP increased when NPP values were less than the corresponding thresholds in Xilin Gol from 2001 to 2014 (Figs. 2 and 3). The largest SC, WY, and WR could be obtained when the NPP got the thresholds on the constraint lines (Fig. 3). WY and WR decreased when SC or SL increased on the constraint lines (Fig. 3). NPP negatively constrained SL for all the years (Fig. 3). WR changed synchronously with WY (Fig. 3).

3.2. Key features of the constraint lines among paired ecosystem services from 2001 to 2014

Overall, the NPP thresholds for the constraint lines of NPP_SC, NPP_WY, and NPP_WR were relatively stable, with small variation coefficients (Fig. 4 and Table A.3). In the box plots, the NPP thresholds for NPP_SC appeared more concentrated than those of NPP_WY and NPP_WR after removing the outliers (years of 2004, 2006, 2012, and 2014) (Fig. 4). The SC thresholds for NPP_SC and WR thresholds for NPP_WR were dispersed, with large variation coefficients (Fig. 4 and Table A.3). Both of the medians of the SC thresholds and the WY thresholds were located in the lower part of the boxes, while the trend was opposite for the WR thresholds (Fig. 4).

Generally, there were large differences in the variations of the coefficients for the k and b values on the constraint lines among paired ecosystem services (Table 4). Both the k and b values for SC_SL showed relatively low coefficients of variation, while the values were high for the other paired ecosystem services (Table 4). Except for NPP_SL and SC_WR, the k and b values for the other paired ecosystem services featured a significant changing trend (Table 4). The constraint effect of SC on SL gradually weakened from 2001 to 2014 with the increasing trend of k values, while SC_WY, SL_WY, and SL_WR showed the opposite trend (Table 4). Similarly, the changing trends of b values divided the paired ecosystem services into two groups. One group included NPP_SL, SC_SL, and WY_WR, with the starting points of the constraint lines gradually falling, and the paired ecosystem services in the other group showed the opposite trend (SC_WY, SL_WY, and SL_WR) (Table 4).

3.3. The correlation between the key features of constraint lines and influential factors

Overall, TEM and WS had no effect on all the key features of the constraint lines between paired ecosystem services with insignificant correlation (Table 5). However, the maximum, the mean, and the difference of maximum and minimum of PPT were the critical factors to shape all the constraint lines of paired ecosystem services, except for SC_SL and WY_WR. Interestingly, these factors of PPT showed a positive correlation with the thresholds and the b values but indicated a negative correlation with the k values (Table 5). The results of NDVI factors appeared more likely opposite to the PPT factors (Table 5).

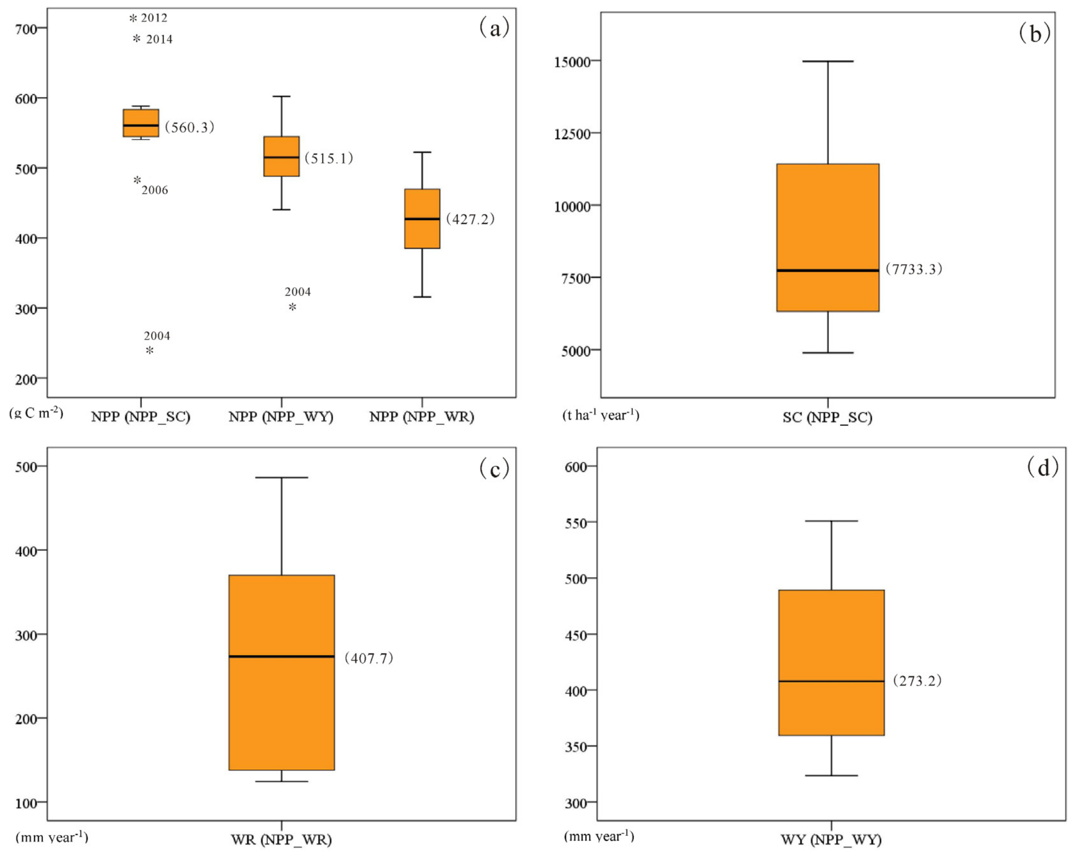

Fig. 4. The box plots of thresholds on the constraint lines of NPP_SC, NPP_WY, and NPP_WR. The values in brackets represent the medians of thresholds. The symbol * indicates the years with outliers (outside of the upper limit (upper quartile plus 1.5 times the interquartile range) and the lower limit (lower quartile minus 1.5 times the interquartile range). Other details are as in Fig. 3.

Table 4
The slopes (k) and constant terms (b) of linear and logarithmic constraint lines.

	NPP_SL		SC_SL		SC_WY		SC_WR		SL_WY		SL_WR		WY_WR	
	k	b	k	b	k	b	k	b	k	b	k	b	k	b
2001	−0.020	29.18	−7.98	78.04	−0.012	315	−57.03	564.7	−5.41	349.3	−6.26	249.3	0.90	9.16
2002	−0.019	26.99	−6.79	64.62	−0.012	334.1	−67.47	657.4	−3.85	358.4	−7.41	298.2	0.85	16.43
2003	−0.039	46.35	−8.71	86.18	−0.011	485.5	−50.68	522.8	−5.07	525	−4.73	241.9	0.51	43.79
2004	−0.030	28.96	−5.94	62.42	−0.005	370.9	−33.91	374.7	−5.65	441.5	−4.40	160.8	0.39	55.22
2005	−0.025	30.17	−7.25	67.85	−0.009	313.3	−26.82	280.2	−7.54	400.7	−3.68	126.9	0.39	44.79
2006	−0.029	32.65	−7.10	71.47	−0.007	347	−31.21	327.9	−6.11	416.6	−3.70	141.2	0.36	51.68
2007	−0.031	31.22	−8.33	80.05	−0.014	301.2	−31.58	314.2	−5.04	358.1	−3.66	136.9	0.34	46.76
2008	−0.015	27.33	−6.89	68.35	−0.007	373.8	−79.33	818.7	−4.24	431.8	−7.87	298.3	0.95	6.03
2009	−0.018	28.80	−6.27	58.19	−0.03	341.3	−62.54	595.1	−4.96	339.8	−6.45	259.4	0.79	22.6
2010	−0.020	30.84	−7.07	70.35	−0.02	413.5	−70.48	709.5	−9.45	510.3	−7.57	322.9	0.86	19.18
2011	−0.028	34.64	−6.86	71.00	−0.008	363.3	−77.23	813.5	−4.78	412.3	−6.69	304.5	0.92	7.44
2012	−0.031	42.51	−9.12	98.85	−0.005	527	−92.24	1050.6	−7.76	592.6	−9.25	463.7	0.84	30.04
2013	−0.031	33.18	−5.42	55.91	−0.007	492.4	−112.6	1168.8	−7.81	517.7	−8.92	372.5	0.79	36.25
2014	−0.017	23.84	−5.01	50.13	−0.014	474.3	−89.51	927.3	−13.52	523.5	−11.87	342.4	0.86	20.78
Mean	−0.03	31.9	−7.05	70.24	−0.01	389.5	−63.05	651.8	−6.51	441.3	−6.6	265.6	0.7	29.30
SD	0.007	6.02	1.19	12.67	0.007	75.5	26.17	280.2	2.57	79.9	2.44	98.7	0.24	17.07
CV	0.23	0.19	0.17	0.18	0.7	0.19	0.41	0.43	0.39	0.18	0.37	0.37	0.34	0.58
Trend	–	↓**	↑**	↓**	↓*	↑**	↓	↑	↓*	↑**	↓**	↑**	↑**	↓**

Note: SD and CV stand for standard deviation and coefficient of variation, respectively. In the line of trend, "–" indicates that there is no rising or falling trend; "↓" indicates the falling trend; "↑" indicates the rising trend. ** indicates that the p value is less than or equal to 0.01, and * indicates that the p value is in the range from 0.01 to 0.05. Other details are as in Figs. 2 and 3.

With regards to the threshold, the factors showing significant correlation included the maximum, the difference between the maximum and minimum, and the mean of PPT and the minimum RA (Table 5). The thresholds of SC, WY, and WR were all positively correlated with the factors of PPT (Table 5). The NPP threshold for NPP_SC was only significantly correlated with the difference between the maximum and minimum of PPT. No significant correlations were found between NDVI factors and the thresholds (Table 5).

With respect to the k value, most PPT factors showed a significantly negative correlation, while the correlation was opposite for NDVI factors (Table 5). For example, the correlation between the mean NDVI and the k value for SC_WY was significantly positive, while the

Table 5
The Spearman correlation coefficients between the key features of constraint lines and the factors of climate and NDVI.

		Thresholds						k							b						
		NPP_SC		NPP_WY		NPP_WR		NPP_SL	SC_SL	SC_WY	SC_WR	SL_WY	SL_WR	WY_WR	NPP_SL	SC_SL	SC_WY	SC_WR	SL_WY	SL_WR	WY_WR
		NPP	SC	NPP	WY	NPP	WR														
maximum	NDVI	0.30	0.16	0.24	−0.05	0.06	0.01	−0.15	−0.18	0.08	0.01	0.2	0.01	−0.11	0.23	0.16	−0.09	−0.01	0.03	−0.01	−0.03
	RA	0.48	−0.13	0.13	−0.35	0.02	−0.13	−0.01	−0.06	−0.01	0.17	−0.2	0.21	−0.19	−0.06	−0.09	−0.37	−0.19	−0.4	−0.15	0.17
	PPT	0.39	***0.72***	***0.59***	***0.95***	0.25	***0.73***	−0.23	0.18	0.44	***−0.68***	***−0.57***	***−0.68***	0.27	0.37	−0.13	***0.93***	***0.7***	***0.9***	***0.71***	−0.06
	TEM	−0.41	−0.07	−0.33	−0.36	−0.24	−0.39	0.11	0.39	−0.17	0.25	−0.01	0.2	−0.32	−0.53	−0.36	−0.3	−0.26	−0.2	−0.32	0.32
	WS	−0.05	−0.03	−0.06	0.24	−0.2	0.12	0.17	0.21	−0.07	−0.17	−0.46	−0.22	0.1	−0.27	−0.33	0.09	0.17	0.17	0.13	−0.05
minimum	NDVI	−0.28	−0.13	−0.17	−0.5	0.02	−0.52	0.13	−0.01	0.23	***0.56***	0.28	***0.57***	−0.28	−0.12	0.01	***−0.54***	***−0.53***	−0.49	***−0.56***	0.27
	RA	−0.08	−0.38	−0.39	***−0.59***	−0.09	−0.47	−0.13	−0.23	−0.4	0.5	0.25	***0.61***	−0.12	0.14	0.29	***−0.65***	−0.53	***−0.68***	−0.45	0.04
	PPT	−0.23	−0.02	0.06	0.38	0.16	0.25	−0.19	−0.28	−0.03	−0.25	0.23	−0.23	−0.03	0.27	0.29	0.44	0.24	0.32	0.26	−0.02
	TEM	−0.49	0.01	−0.49	−0.14	−0.3	−0.47	0.06	0.17	−0.01	0.26	0.29	0.25	−0.18	−0.37	−0.14	−0.24	−0.28	−0.02	−0.39	0.16
	WS	0.2	−0.13	0.3	0.01	−0.16	0.31	0.29	0.35	−0.18	−0.21	−0.25	−0.17	0.32	−0.05	−0.33	−0.02	0.23	−0.25	0.24	−0.29
mean	NDVI	−0.17	0.45	0.01	0.45	0.27	0.14	−0.19	−0.28	***0.67***	−0.14	0.09	−0.19	0.11	0.31	0.37	0.51	0.18	***0.62***	0.15	0.01
	RA	0.43	−0.17	0.03	−0.44	−0.12	−0.21	0.01	0.01	−0.16	0.24	−0.06	0.34	−0.06	0.02	−0.07	−0.53	−0.27	***−0.57***	−0.24	0.02
	PPT	0.02	***0.62***	0.25	***0.84***	0.09	***0.62***	−0.24	0.09	0.48	***−0.67***	−0.23	***0.67***	0.25	0.26	0.02	***0.93***	***0.68***	***0.88***	***0.66***	−0.06
	TEM	−0.45	−0.01	−0.51	−0.29	−0.38	−0.42	0.08	0.28	−0.05	0.22	0.14	0.2	−0.19	−0.48	−0.24	−0.3	−0.24	−0.13	−0.33	0.2
	WS	0.07	−0.06	0.18	0.19	−0.16	0.22	0.25	0.27	−0.23	−0.24	−0.5	−0.28	0.06	−0.3	−0.39	0.06	0.23	0.06	0.2	−0.05
Maximum-minimum	NDVI	0.37	0.23	0.2	0.4	−0.08	0.46	−0.22	−0.07	−0.13	***−0.54***	−0.16	−0.5	0.24	0.2	0.1	0.46	0.51	0.42	0.51	−0.26
	RA	0.32	0.2	0.5	0.3	0.08	0.34	0.24	0.31	0.35	−0.34	−0.28	−0.44	0.01	−0.25	−0.49	0.31	0.35	0.34	0.29	0.03
	PPT	***0.59***	***0.68***	***0.56***	***0.66***	0.05	***0.65***	−0.03	0.31	0.5	***−0.61***	***−0.66***	***−0.61***	0.35	0.16	−0.29	***0.61***	***0.62***	***0.62***	***0.63***	−0.13
	TEM	0.14	−0.17	0.28	−0.18	0.02	0.25	0.26	0.43	−0.16	−0.13	−0.39	−0.2	0.08	−0.25	−0.46	0.01	0.17	−0.18	0.2	−0.04
	WS	−0.05	−0.03	−0.06	0.24	−0.2	0.12	0.17	0.21	−0.07	−0.18	−0.46	−0.22	0.1	−0.27	−0.33	0.09	0.17	0.17	0.13	−0.05

Note: the bold numbers represent the correlation coefficients that are significant (P value ≤ 0.05). DF is equal to 12. Other details are as in Figs. 2 and 3.

correlations between the PPT factors and the k values for SC_WR, SL_WY, and SL_WR were significantly negative (Table 5). The k values of NPP_SL, SC_SL, and WY_WR were not related to any of the influential factors (Table 5).

There were no factors significantly related with the b values for NPP_SL, SC_SL, and WY_WR (Table 5). The significantly related factors of PPT had a strong positive correlation with the b values for SC_WY, SC_WR, SL_WY, and SL_WR. However, the significantly related factors of NDVI and RA showed a negative correlation with the b values of the constraint lines, except for the average NDVI with the b value for SL_WY (Table 5).

4. Discussion

All the scatter points of the ten paired ecosystem services appear to be similar to "scatter clouds" from 2001 to 2014 in Xilin Gol, which indicates that the constraint line approach is indeed effective for describing the relationship among paired ecosystem services (Hao et al., 2017b; Medinski et al., 2010; Thomson et al., 1996). The constraint lines of the ten paired ecosystem services show stable shapes, although some constraint lines do not fit the scatter clouds very well (Figs. 2 and A.1, and Table 3). The negative linear constraint lines for SC_WY, SL_WY, and SL_WR in the study appear to be different from the logarithmic and waved types in the research of Hao et al. (2017b). This difference may be caused by the scale dependence of the constraint effect between ecosystem services (Hao et al., 2017b). The relationships of ecosystem services on the constraint lines are consistent with the tradeoffs or synergies. For example, SC and SL on the logarithmic constraint line and NPP and SL on the negative linear constraint line indicated that they changed inversely; WY and WR on the positive constraint line changed synchronously; but NPP and SC on the hump-shaped constraint line may be found unrelated.

4.1. The underlying mechanisms of shaping the constraint lines among paired ecosystem services

The key feature of threshold indicates a change in the direction of the constraint effect among paired ecosystem services on the two sides of the constraint line (Seidl et al., 2016; Wissel, 1984). The thresholds of SC for NPP_SC and WR for NPP_WR were unstable and exhibited large variations (Fig. 4), which was mainly caused by the dynamics of PPT. Most of the k and the b values of the constraint lines for paired ecosystem services had significant changing trends, which indicates that they may be impacted by some factors, as shown in Table 5.

The constraint lines were shaped by multiple factors in most cases (Medinski et al., 2010; Mills et al., 2009; Thomson et al., 1996). The values on the constraint lines represent the maximums or the minimums of the response variables (Evanylo and Sumner, 1987; Wang et al., 2015), and they may be related to the maximum or minimum values of many factors (Table 5). For example, on the hump-shaped constraint lines between NPP and SC, the difference between the maximum and minimum of PPT is the factor that determines the position of thresholds on the x-axis (NPP values). Meanwhile, the maximum and mean as well as the difference between the maximum and minimum of PPT determine the height (SC thresholds) of the constraint lines. The results are consistent with the analysis in other researches (e.g., Guerra et al., 2016; Hao et al., 2017b; Jia et al., 2014). However, the factors of NDVI were unrelated to the thresholds (Table 5). The reason for this result may be that although NDVI was directly involved in the ecological processes of the constraint effects, it was not the trigger that caused the change in interaction direction (Hao et al., 2017b; Jia et al., 2014; Piao et al., 2006). With no climate factors and NDVI significantly correlated with the key features of NPP_WR, the factors such as terrain and soil may shape their constraint lines (Hao et al., 2017a).

The k values and the b values jointly represent the shapes and positions of the linear and logarithmic constraint lines. The factors positively correlated with k values may weaken the constraint effect because all k values are less than 0 except for WY_WR, whose k values are not significantly related with any of the factors. For example, the minimum NDVI weakens the constraint effect of SC on WY because high vegetation coverage promotes soil conservation while reducing surface runoff (Cao et al., 2009; Fryrear et al., 2001). The maximum PPT enhances the constraint effects of SL_WY and SL_WR because WY and WR on the constraint lines increase with an increase in the maximum PPT, but PPT suppresses SL (Evanylo and Sumner, 1987; Fryrear et al., 2001; Sharp et al., 2015). Guo et al. (2013) also mentioned that precipitation has an inhibition role on soil erosion by wind in agricultural ecosystem of northern China.

For the positions at the starting points of the constraint lines, the b value mainly indicates the maximums of WY and WR for the paired ecosystem services of SC_WY, SC_WR, SL_WY, and SL_WR. The larger the values of the starting points on the y-axis, the smaller the constraint effect between the bi-variables when the variable on the x-axis is almost equal to 0. The maximum and the mean of PPT weaken the constraint effects of SC_WY, SC_WR, SL_WY, and SL_WR, while the minimum NDVI strengthens them at the starting points of the constraint lines. The reason for this result may be that at the starting points, i.e., when the values of SC and SL are very small, PPT determines the maximum values of WY and WR (Zheng et al., 2014), but the minimum NDVI results in the decreases in WY and WR over the whole study area.

Bennett et al. (2009) proposed that the relationships of ecosystem services are caused by the roles of the same drivings and the interactions between services. Xilin Gol is located in arid and semiarid areas. Water availability of grassland ecosystem is mainly determined by the patterns of PPT. Additionally, PPT is the most important climatic factor driving the dynamics of the ecosystem services of NPP, SC, SL, WY, and WR (Hao et al., 2017a). Therefore, the factors of PPT are critical to shape the features of the constraint lines between paired ecosystem service.

4.2. Implications for grassland ecosystem management

Except for the PPT factors, the minimum NDVI is also critical to determine the key features of slopes and constant terms on the constraint lines. Therefore, PPT and NDVI should be the two main considerations in promoting grassland ecosystem service management.

The direction of the interactions between ecosystem services would change when the constraint services approach the thresholds. Therefore, policy makers should be cautious in formulating policies that would otherwise cause mutations in some ecosystem services. As one of the supporting ecosystem services, NPP is positively and significantly correlated with NDVI (Hao et al., 2017a; Zhu et al., 2007). NDVI can be changed easily by human activities. The NPP thresholds for NPP_SC, NPP_WY, and NPP_WR are critical references to achieve a win-win situation of NPP, SC, WY, and WR, and they should be considered in ecosystem management. When NPP exceeded the thresholds, the other three ecosystem services decreased. Policy makers can apply the stable change ranges of NPP thresholds in planning the surface vegetation cover, including the species features and composition for the purpose of vegetation restoration (Bai et al., 2004; Hao et al., 2017a). Indeed, the enhanced constraint effects of SC_WY and SC_WR are unexpected in reality so that the factors that are negatively correlated with the k values should be reduced, such as the difference in the maximum and minimum of NDVI. Therefore, policy makers should try to decrease the difference of NDVI in Xilin Gol, namely, that overgrazing should be avoided. Because soil loss by wind is not beneficial to humans, people can enhance the constraint effects of SL_WY and SL_WY by decreasing the minimum NDVI. Therefore, by combining the suggestion of the SC_WY, SC_WR, SL_WY, and SL_WR, policy makers do not have to pursue a high NDVI for all the areas in Xilin Gol.

Understanding the potential factors shaping the constraint effects

among ecosystem services is an important step in ecosystem management. However, it should be noted that the constraint effects among ecosystem services are scale-dependent and context-dependent (Hao et al., 2017b). The results achieved in this study should be taken with caution when they are used in other regions. In this study, we mainly explored the impacts of climatic factors and NDVI on the interaction between paired ecosystem services, which indicated that the influencing mechanism is complex. How these factors individually and jointly impact the relationship of ecosystem services should be further explored when this approach is applied in other regions.

5. Conclusions

The constraint effects between paired ecosystem services and associated key features, including thresholds, k value, and b value are shaped by climate factors, NDVI, and other factors. Although Xilin Gol has experienced grassland restoration over a long period, the shapes of constraint lines between paired ecosystem services were unchanged from 2001 to 2014, while the values of threshold, k, and b varied. PPT is the most important factor that shapes the constraint effect between paired ecosystem services in Xilin Gol. In most cases, PPT does not only strengthen the constraint effect among ecosystem services but also increase the positions of the starting points of the constraint lines. NDVI has no effect on thresholds but determines the strength of the constraint effects of SC_WY, SC_WR, and SL_WR. The relatively stable change ranges of NPP thresholds can be used for managing the surface vegetation to achieve a win-win situation. Additionally, policy makers can adjust surface vegetation with the aim of increasing (negative correlation between k value and NDVI) or decreasing (positive correlation between k value and NDVI) the strength of the constraint effects of SC_WY, SC_WR, and SL_WR.

Quantifying the characteristics and influential factors of the constraint effects among ecosystem services can encourage policy makers to develop effective measures of ecosystem management.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2019.01.080.

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